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A state of art review on the performance of transpired solar collector

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ABSTRACT

Utilisation of solar radiation to heat air for various purposes, e.g. ventilation, pre heat, process air heat and their applications has attracted more and more interests. Wide range of applications adapted for different climates and in different building types ranging from houses to large industrial buildings. Recently in many European countries, USA and Canada this concept developed rapidly. Transpired solar collectors (TSCs) have proven reliable for various applications, e.g. heating spaces, providing warm ventilation air, supplying domestic hot water in summer, etc.

Present paper consists of introduction to various types of TSCs, working principle, research literature for performance and modelling. Further various models have also been discussed and compared. The literature has shown that the most critical factors affecting TSC efficiency are wind velocity, flow rate, porosity, absorptivity and porosity.

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1. Introduction

Since increasing carbon dioxide (CO_2) emissions are believed to be contributing to our changing climate then sooner or later emissions from buildings must be tackled [1]. Academics and policy makers agree that buildings across the European Union represent about 39–40% of the gross energy consumption in Europe and emit approximately 35% of carbon dioxide emissions [2]. Achieving significant reduction in the energy consumption of buildings is a significant challenge for the European Union and yet offers hope for the future. Out of the emerging policy agenda – especially the Energy Performance of Buildings Directive (EPBD) has arisen a range of solutions to reduce the energy demand of buildings, new calculation methods for energy performance, minimum requirements for new builds, energy audits, boiler inspections, renewable energy integration and energy certification.

Part of the solution of this ever increasing problem can be solar thermal systems, as solar thermal systems harness solar energy for thermal energy. Solar thermal collectors can be classified as low, medium and high temperature collectors.

2. Solar collectors

There are many usages of solar energy; among them one of the most potential applications of solar energy is in the form of solar

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Nomenclature

Q_u	collector useful gain (Watt)
A	area (m^2)
F_{c-g}	view factor from collector to ground
T	temperature (°C)
S	absorbed radiation (Watt)
$\dot{m}$	flow rate (kg/s)
C_p	specific heat capacity
h	heat transfer coefficient (W/m^2 K)
Nu_D	Nusselt number
K	thermal conductivity (W/m K)
P	pitch (m)
D	diameter of hole (m)
Re_D	Reynolds number
V	air velocity entering in to the holes (m/s)
v	wind velocity
$\in$	heat exchange effectiveness
ε	collector infrared emittance
σ	Stefan-Boltzmann constant
NTU	number of transfer units
ρ	density of air (kg/m^3)
σ_p	porosity
μ	dynamic viscosity of the fluid (kg/ms)
α	absorptivity

Subscripts

c	collector
a	ambient
f	fluid
o	outlet
HX	heat exchange
r	radiative

air heaters. Solar air heaters are used for many purposes, e.g. drying agricultural, textile and marine products, and heating of buildings to maintain a comfortable environment during [3]. Among them flat plate collectors [4–9] used to be most popular type of solar collector for many years. These flat plate collectors are typically consists of glazing, solar absorber plate mounted on insulated back surface (Fig. 1).

Many designs for solar air heated have been reported and discussed in the literature [7–12], e.g. bare plate, back-pass, glazed, unglazed, covered, uncovered, perforated, un-perforated, single pass, double pass, triples pass etc. Fig. 2 shows few of the solar air collectors reported in literature.

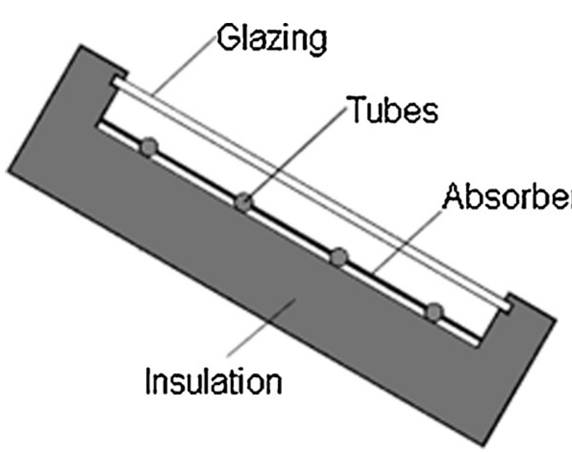

Fig. 1. Schematics of a flat plate solar air collector.

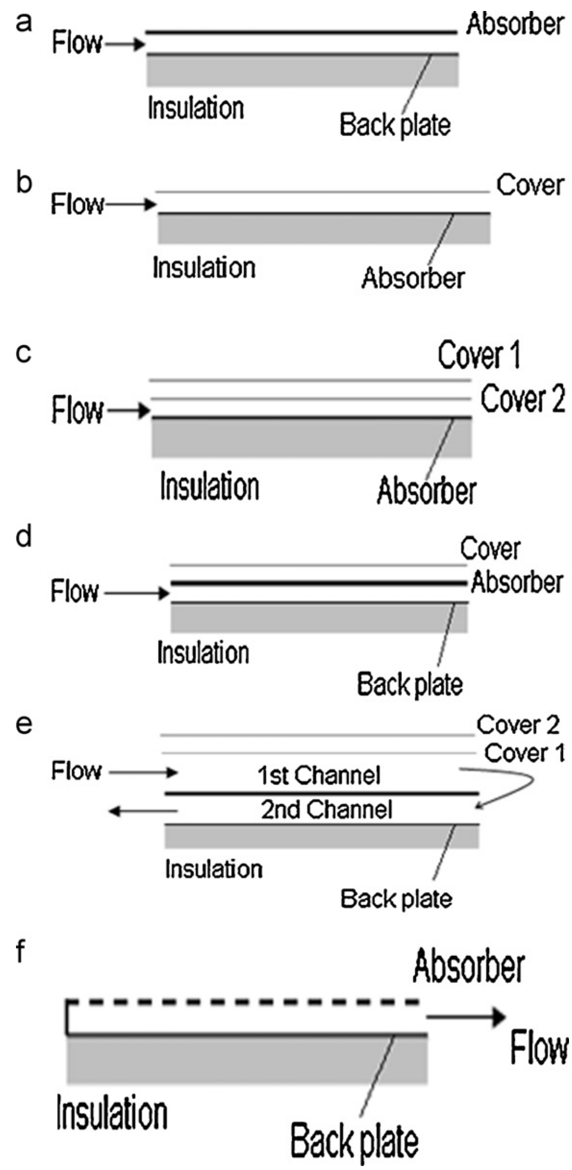

Fig. 2. (a) Bare plate solar air heater [8–11]. (b) Single cover solar air heater [7,9,10]. (c) Double cover solar air heater [7,10]. (d) Single cover solar air heater [7,10]. (e) Double pass type solar air heater [10,12]. (f) Transpired solar collector [13,24,25].

Fig. 2a shows bare plate single channel solar air heater; air flow between insulation and absorber plate. In these types of solar air heater heat loss from surface of the absorber were significant, so other designs were proposed. Fig. 2b shows single cover solar air heater system, which reduces the top losses from the absorber and also benefit in increasing the temperature by greenhouse effect. Double cover single channel air heater (Fig. 2c), single cover air heater (with different design, Fig. 2d), double pass solar air heater (Fig. 2e) are also shown. Transpired solar air heaters (Fig. 2f) are also modified form of solar air heaters with increased benefit in terms of usage either as standalone system or building integrated. Transpired solar collectors (TSCs) are also often called unglazed transpired solar collectors (UTCs); however, this does not differentiate the transpired solar collector from a bare plate solar heater represented in Fig. 2a. Transpired collectors operate at low temperature, which leads to high conversion efficiency and possibility of integration with other renewable energy sources. Fig. 3 shows installed transpired solar collector in green and black colours at SBEC, Tata Steel, Shotton works, UK.

Fig. 3. Transpired solar collector at SBEC, TATA Steel, Shotton works, UK.

3. Transpired solar collectors (TSCs)

Transpired solar collectors are relatively new for Europe but have been widely used in Canada and USA. TSC is highly efficient collector system particularly for preheating fresh air.

3.1. Working principle

TSCs are an unglazed once-through solar air system with a perforated absorber layer. TSCs use solar energy to heat the absorber surface, which transmits thermal energy to the ambient air. The absorber surface is generally a metallic sheet (usually steel or aluminium), which can be integrated to the building façade. The contact surface between the metal skin and air is increased by drawing air through the multiple small perforations into the cavity between the skin and façade. Finally heated air is drawn into the building to provide space heating. During summer season the warm air in the cavity can be released using a by-pass damper to avoid over heating inside the building or can be used for water heating in order to maximise the utilisation of TSCs.

3.2. Collector construction and its parameters

In a TSC system, solar energy collecting system is created by fixing a perforated sheet at around 100–300 mm from a back sheet [13]. The back sheet can be building envelope in case of building integrated TSC (Fig. 4) or a non-perforated insulated sheet in case of standalone system. The space between the absorber (perforated sheet) and back plate is sealed to create an air channel also known as a plenum. The perforations generally cover a very small fraction of total area of TSC (also known as porosity). It has been reported that porosity of TSC varies between 0.5% and 2% of the collector area [14]. At the top of the back sheet, there is an outlet which leads to ducting system having fan. The fan sucks the air through the collector, which draws ambient air to pass through the holes

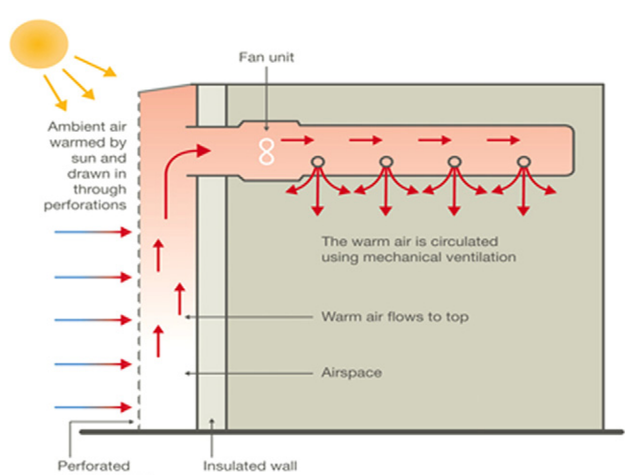

Fig. 4. Building integrated transpired solar collector.

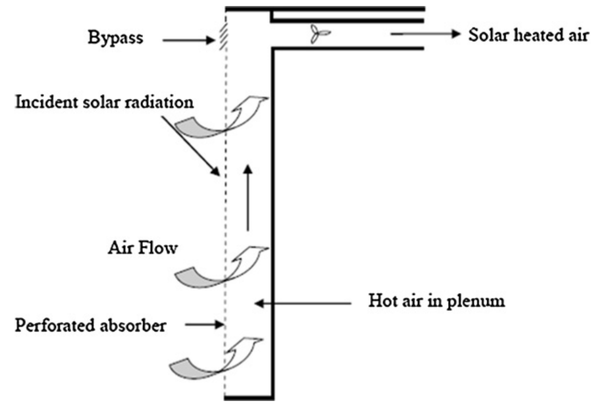

Fig. 5. Schematics of standalone transpired solar collector.

and collect heat from the absorber surface and the heated surface boundary layer. Then solar heated air is drawn up through the air channel and goes to distribution ducting. The basic heat transfer theory between air and collector is based upon various approximations, e.g. homogenous flow, steady state condition and many others [15]. It has been reported that around 62% of heat gain is obtained from the warm surface boundary layer on the front surface of the collector, 28% occurs in holes and the remaining 10% from the back surface of collector [16,17]. There are many parameters which affect the performance of TSC [13,18], e.g. porosity, type of grid the holes form, geometry of holes, plenum dimensions, material and absorptance of the collector, approach velocity, plenum velocity, surface coatings, wind effect and profile of collector. Different parameters have benefits in changing location and climate. Circular, slotted, triangular holes are reported in literature.

3.3. Various types of transpired solar collector (TSC)

3.3.1. Stand alone transpired solar collector

Transpired solar collectors (TSCs) are solar thermal systems and a basic TSC consists of a perforated absorber fixed to a bottom plate with sealing around the edges (Fig. 5). Leon and Kumar [15] has carried out detailed study of stand alone TSC. In a stand alone TSC perforated absorber and back plate both are exposed to ambient environment (Fig. 5). Stand alone TSC have modularity in terms of their application they can be used for wide range of application from ventilation pre-heat air to agricultural applications.

3.3.2. Hybrid and building integrated transpired solar collector

Mostly solar energy systems have their limitations in terms of their potential to make their demand fulfil. So there is need to combine more than one system at a time in order to maximise the utilisation of resources. Hybrid means mixing of more than one. There are various technologies, e.g. photovoltaic (PV), storage (phase change material, granite, etc.) and water heating which can be integrated into a hybrid transpired collector. IEA report [19] finds that PV system can last 50 years; integration of the PV system with building integrated TSC can be good option where TSC also have long life extending up to 50 years typically. Building envelope cladding or outer layer of roof (BIPV) replacing, for example roof tiles or asphalt shingles. BIPV has a significant advantage over modular systems that they are an add-on to the building envelope and reduces the balance of system cost (BOS) and enhanced durability of building envelope when compared with attached PV systems [20]. Mostly PV operates in the efficiency range of 6–18% and rest of energy is lost in terms of unused heat generation, which adversely affects the efficiency of PV systems [21]. In order to take useful heat generation from PV, BIPV/T systems are designed. In BIPV/T

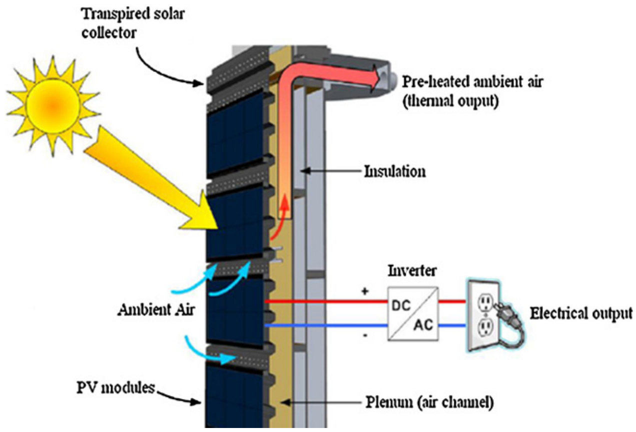

Fig. 6. Schematics of building integrated BIPVT. Modified [21].

systems a cooling fluid air or water is used. Various geometries of BIPV/T systems are reported in literature. Fig. 6 shows schematics of BIPV/T systems using air as cooling fluid [21].

The combination of TSC and PV panels on facades is promising for building applications where there is significant need to heat ventilation air in winter. Since many non-domestic buildings use heat recovery ventilators to extract maximum useful heat from exhaust air, excess heat from BIPV/T system can be utilised for space heating or possibly hot water. A potential advantage of BIPV/T systems is that during summer months heating is not required, so the production of electricity may be an added bonus.

Another unique design of BIPV/T is proposed by Anderson et al. [22]. The system examined is directly integrated into the roof of a building made from standing seam or troughed sheet. Standing seam and troughed sheet roofs are typically made from aluminium or coated steel though other metals can also be used. They are rolled and pressed into a shape that gives the roof product stiffness, strength and when assembled are weather proof. This system also utilises high thermal conductivity materials used in those roofing system for form the BIPV/T system. During the manufacturing process in addition to the normal troughed shape, passageways are added for the thermal cooling medium to travel through (Fig. 7). The passageways formed in the trough are subsequently enclosed by the cover, thus forming a tube to which heat can be transferred. The flow has an inlet and outlet at opposite ends of the trough.

There are many other geometries also reported. Fig. 7 shows roof mounted PV/T system developed by solar wall [23].

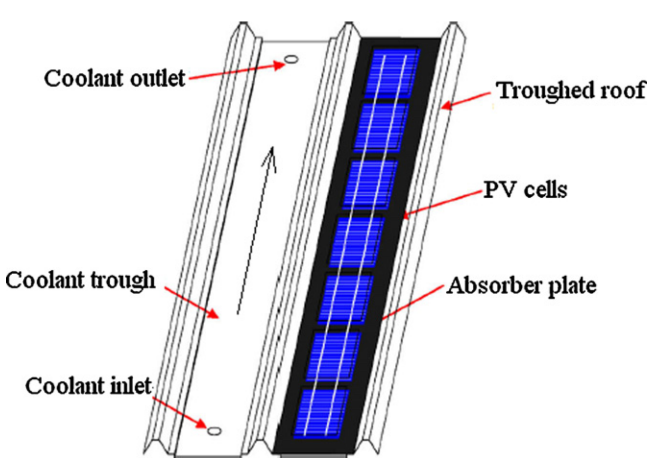

Fig. 7. Roof mounted BIPVT collector [22].

Fig. 8. Roof integrated PV/T system [23].

This roof mounted BIPV/T consists of solar PV/T system, hot air duct and air handling unit. This system is appropriate for a flat roof where enough space is available to install the system. PV can also be integrated directly onto the roofs as done for building walls (Fig. 8). Fig. 9 shows schematic of another roof mounted TSC, which utilises granite/ballast or phase change material (PCM) for heat storage at the base of the structure. The base of the TSC also provides stability from wind pressure in case of high wind. The stored heat can be released to the building at night, so extending the effective operation time of the hybrid system and will be specially useful in buildings such as hospitals with a constant fresh air requirement.

4. Performance of transpired solar collectors

The thermal performance of transpired solar collectors is very complex where different parameters dominate in different situations, e.g. effect of cross wind is more dominating while collector is operating at high temperature rise and low efficiency [13,17]. Thermal performance of TSC depends on various factors summarised below:

climatic conditions: ambient temperature, solar radiation, wind effect, rain, humidity, sky temperature;
site constraints: orientation, tilt, surroundings of the site;
geometry of collector: size of collector, cavity dimensions, surface coatings, absorptance, material, porosity;
geometry of holes: pitch, dimensions (hole diameter), hole shape, pattern;
building parameters (excluding stand alone): wall *U* value, area of wall; and
load characteristics: high temperature rise, low temperature rise, process air, re circulation, fan velocity.

Studies on TSC to investigate the heat and air mass transfer, efficiency, airflow distribution and pressure drop have been carried out since 1991.Various studies have been carried out to study the thermal performance of standalone as well as hybrid and building integrated systems, these are presented in chronological order in Table 1. Thermal performance study of TSCs can be classified in three separate sections:

- mathematical modelling and physical experimental study;
- simulations including computational fluid dynamics (CFD); and
- parametric studies.

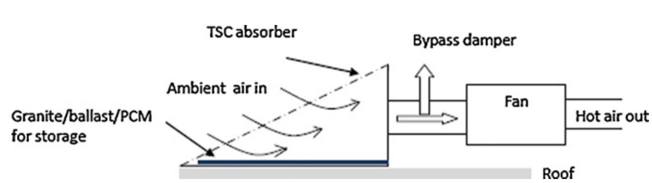

Fig. 9. Schematics of roof integrated TSC with storage.

Table 1
Summary table for various models and study reported in literature.

Publications/Refs.	Objectives and method used	Type of TSCs	Software/model used	Conclusions	Special findings
Kutscher et al. [24]	Development of an analytical model and tests results	TSC	Mathematical	Efficiency of collector is mainly dependent on absorptivity, flow rate and heat exchange effectiveness	Efficiency can slightly increase or decrease with variations in radiation levels
Kutscher [13]	Heat exchange effectiveness and pressure drop for air flow also study of crosswinds	TSC	Mathematical	With low flow rate values rise in collector temperatures are higher. Maximum collector efficiency achieved at no wind condition	Wind effects are more important while collector is operation for high temperature rise and low efficiency regime.
Summers [25]	To predict energy savings this is comprised of the active solar gain, the recaptured wall loss and reduced wall loss. Parametric studies for system operation. Simulation is carried out.	TSC	TRNSYS	The TSC systems are competitive with electric heating but not with oil or gas heating. They are also cost effective for new builds.	Economic potential of UTC for different sectors, e.g. commercial, residential, agricultural and industrial
Gunnewiek et al. [28]	Flow distribution analysis using CFD	TSCs	TASCflow 2.2	For analysed models suction velocity needs to be small in order to increase the efficiency	Parametric study for some models and it has been found that wide plenum and low dynamic resistance can lead to high efficiency.
Daymond and Kutscher [29]	To develop a computer model which would run quickly on a PC and allow designers to easily adjust geometric parameters in order to study UTC	TSC	Pipe network modelling algorithm	Modelling provided flow rates and temperatures of an unglazed transpired solar collector	Acceleration pressure drop between two pipes is deduced based on the flow rates in nearby pipes. Study provided a model of UTC that is useful both for design tool and research.
Arulanandam et al. [30]	To study heat exchange effectiveness and CFD analysis for constant temperature and solar radiation	TSC	CFD, Statistical analysis SAS, TASCflow	If TSC are made from materials with low conductivity such as plastics, acceptable efficiency can be achieved	Potential for low conductivity absorbers with low porosity and low flow rate
Hollick [27]	To study commercial scale solar drying	TSC	Design concept	Each square meter of solar panel can dry varying amounts of produce depending on the initial and final moisture contents.	The proposed solar seed drying in India would payback within approximately two years. This indicates that solar drying is cost effective in existing drying operations.
Van Decker [16]	Experimental investigation for heat exchange effectiveness	TSC	Mathematical and Physical Experiment	Maximum heat transfer occurs at face heated boundary layer of TSC	28% heat transfer occurs during air pass through holes,10% at the back surface of absorber plate whereas maximum 62% heat transfer occurs at the face of heated boundary layer on the front face of the collector
Fleck et al. [31]	Parametric experimental study for the effect of ambient wind	TSC	Physical Experiment	UTCs are not well suited for high rise residential buildings due to small area and low flow rate	Hourly efficiency were found to be independent of incident solar radiation for radiation level above 200 Wh/m^2
Gunnewiek et al. [32]	Effect of wind on the flow distribution	TSCs	TASCflow 2.2	Windy condition can result in reverse suction in windy condition	Increase in suction rate would avoid reverse flow in windy condition

Table 1 (*Continued*)

Publications/Refs.	Objectives and method used	Type of TSCs	Software/model used	Conclusions	Special findings
Gawlik and Kutscher [33]	Wind heat loss from corrugated, transpired solar collectors	TSCs	Fluent	Wind loss is low for attached flow	The boundary layer dynamics is very important to determine heat loss coefficient.
Zomorodian and Woods [34]	Sensitivity analysis for various input parameters on collector efficiency	Hybrid TSC TSC + glass plate collector	Mathematical modelling	High absorbing efficiency can be achieved by combining glass plate collector to TSC	While putting once through glass plate on top of TSC an absorbing efficiency of 82% can be achieved
Biona et al. [35]	Mathematical modelling for performance curve generation of TSC	TSC integrated to drying chamber	Mathematical modelling	Performance curves showed that collector efficiency and temperature rise varied linearly with plenum depth showing a directly proportional relationship	Collector efficiency tends to decrease with increasing hole diameter for plates with small pitch distances whereas it produces very minimal effects of moderate pitch distances.
Delisle and Collins [20]	Predicting the performance of PV/thermal TSC	TSCs/PV	TRNSYS	The electricity produced may be significantly higher than the reduction in useful thermal energy.	Thermal energy collected is not much affected by adding PV. However, significant technical challenges remain in the development of UTC with PV cells directly integrated on it.
Leon and Kumar [15]	To study standalone TSC	Standalone TSC	Mathematical	Heat exchange effectiveness is mainly influenced by solar absorptance, collector pitch and approach velocity	The results of the model have been used to develop nomograms, which can be a valuable tool for a collector designer in optimising the design and thermal performance of TSC.
Anderson at al. [22]	Performance of building integrated thermal system	BIPV/T system	Physical Experiment/mathematical	The fact that the collector base material made little difference to the thermal efficiency of the BIPVT suggests that lower cost materials, such as steel, could be utilised for these systems.	Finally, there appears to be significant potential to utilise the low natural convection heat transfer in the attic at the rear of the BIPVT to act as an insulating layer rather than using additional insulation material in order to achieve more savings
Motahar and Alemrajabi [36]	Analysis of Unglazed Transpired Solar Collectors based on Exergetic Performance Criteria	Building integrated TSC	Mathematical	The effect of several parameters on exergy efficiency was explored. Hole diameter and pitch, incident solar radiation and air approach velocity were all found to have a significant impact. A maximum exergy efficiency of 2.28% is obtained.	In spite of all the thermal performance advantages, the exergetic efficiency of the TSC is significantly lower than its energetic efficiency.
Cordeau and Barrington [37]	Performance of unglazed solar ventilation air pre-heaters for broiler barns	TSC integrated to broiler barns	Physical experiment	Besides the level of incoming solar radiation, wind velocity was found to be the main factor affecting the energy recovery efficiency of the unglazed solar air pre-heaters.	The average efficiency of the solar air pre-heaters was 65% for wind velocities under 2 m/s, but dropped below 25% for wind velocities exceeding 7 m/s.

Table 1 (*Continued*)

Publications/Refs.	Objectives and method used	Type of TSCs	Software/model used	Conclusions	Special findings
Athienitis et al. [21]	Consideration of BIPV/T and UTC systems for building facades Prototype developed	PV integrated TSC	Prototype experiments Simple mathematical model	The ratio of PV area coverage may be selected based on the fresh air heating needs of the building, the value of electricity generated and the available surfaces. The combination of TSC with PV is promising for building applications where there is significant need to ventilation in winter.	The value of generated energy for BIPV/T system is 7–17% higher than UTC

4.1. Mathematical modelling and experimental study

A novel unglazed air heating transpired collector has been studied both analytically and experimentally [13,24,25]. TSC systems are often very large and as a result the convection loss from the surface is very small (if the suction flow rate per unit area is sufficiently large, convection losses only occur at edges where the ambient air is not incorporated into the heating system). Consequently, the collector losses consist primarily of radiation to the surroundings [26]. Assumed view factor from the collector to ground is 0.5. The collector use full gain (Q_u) is the difference between the absorbed radiation and the radiation losses:

$$Q_u = A_c[S - \varepsilon\sigma F_{c-g}(T_c^4 - T_\alpha^4) + \varepsilon\sigma(1 - F_{c-g})(T_c^4 - T_{sky}^4)] \tag{1}$$

The collector temperature is found from an effectiveness relating the collector useful energy gain to the maximum possible energy gain:

$$\frac{Q_u}{\dot{m}c_p(T_c - T_\alpha)} = 1 - e^{-NTU} = 1 - \exp\left[-\frac{h(A_C - A_{holes})}{\dot{m}C_p}\right] \tag{2}$$

Here number of transfer unit (NTU) can be defined as

$$NTU = \frac{h(A_c - A_{holes})}{\dot{m}c_p} \tag{3}$$

where $h = \frac{Nu_D K_f}{D}$; $Nu_D = 2.75\left(\frac{p}{D}\right)^{-1.21} Re_D^{0.43}$; $Re_D = \frac{\rho V_{holes} D}{\mu}$; $V_{holes} = \frac{0.05\times A_c}{\rho A_{holes}}$; and $\rho_p = \frac{A_{hole}}{A_{triangle}} = \frac{A_{holes}}{A_c} = \frac{\pi}{2\sqrt{3}}\left(\frac{D}{p}\right)^2$

From above these equations a non-linear equation for collector temperature can be written as

$$S - \varepsilon\sigma F_{c-g}(T_c^4 - T_a^4) + \varepsilon\sigma(1 - F_{c-g})(T_c^4 - T_{sky}^4) = \frac{\dot{m}}{A_c}C_p(T_c - T_a)(1 - e^{-NTU}) \tag{4}$$

Which can be re-arranged to:

$$S - \varepsilon\left[T_c^4 - \frac{(T_a^4 + T_{sky}^4)}{\sigma}\right] = \frac{\dot{m}}{A_c}C_p(T_c - T_a)(1 - e^{-NTU}) \tag{5}$$

In the above equation everything but T_c is known. Solving above equation for T_c and using the value in

$$Q_u = A_c\left[S - \varepsilon\left(T_c^4 - \frac{(T_a^4 + T_{sky}^4)}{\sigma}\right)\right] \tag{6}$$

Now useful energy can also be written as

$$Q_u = \dot{m}C_p(T_o - T_a) \tag{7}$$

Solving equation outlet temperature can be written as

$$T_o = T_a + \frac{Q_u}{C_p^{\dot{m}}} \tag{8}$$

Further the efficiency of the collector can be calculated using heat exchange effectiveness to incorporate wind effects [13,24] which can increase the heat transfer coefficient at heated boundary layer leading to increase collector performance.

$$\eta = \frac{\alpha}{\left[1 + ((h_r/\in_{HX}) + h_c/\rho C_p v)\right]} \tag{9}$$

where $\in_{HX}$ is the heat exchange effectiveness. Efficiency has been calculated for different flow rates and wind speeds. The results are illustrated in Fig. 10.

Fig. 10 has been reproduced [13] to see the change in efficiency with flow rate. Maximum efficiency is occurring at no wind condition where as efficiency is increasing as the flow rate is increased. It has also been found that TSC can achieve efficiencies up to 80%.

Modelling approaches mainly focus on heat transfer between plenum air and plenum surfaces (back plate and absorber) [13,15]. Early stage theoretical model was developed [17,24] later on based on these models analysis of TSC is carried out [33]. They [13,15,17,24] have found out that non-uniform temperature distribution on absorber plate does not have significant impact on thermal performance of TSC. So it can be assumed in the modelling that collector temperature is homogeneous. Also [29] they have assumed air flow through the holes to the plenum is uniform even though this could not be the case (this aspect is studied further using CFD [28,30,32] and discussed in Section 4.2. The basic heat loss theory for unglazed transpired collector is explained in detail

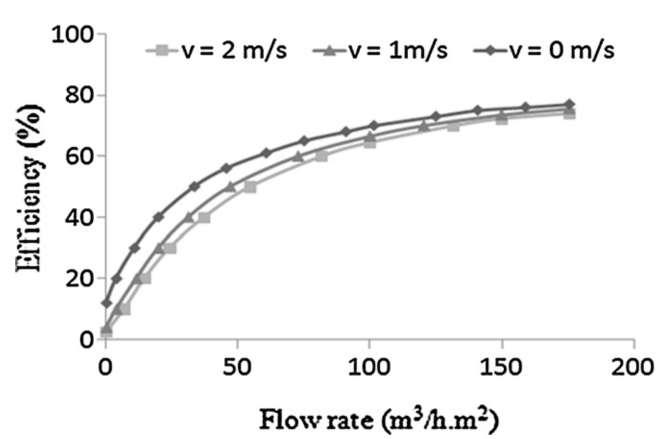

Fig. 10. Variations in Collector efficiency with flow rate (produced using Eq. (9)).

by various researchers [38,39,40,41]. An empirical model for thin plates with circular holes on a triangular layout has been presented by Kutscher [13], with the wind parallel to the plate. Kutscher and Van Decker [13,18] measured heat exchange effectiveness on thin and thick plates with circular holes on a square or triangular layout over a range of parameters and presented a correlation for heat exchange effectiveness by fitting the measured data. Further Van Decker et al. [16] presented a paper on measurements of heat exchange effectiveness for the case where the plate is perforated with circular holes on either a square or triangular layout, covering a range of wind speeds extending from 0 to 5 m/s. From this work he was able to report that 28% heat transfer occurs during air pass through holes, 10% at the back surface of absorber plate whereas maximum 62% heat transfer occurs at the face of heated boundary layer. Authors also presented a predictive model for heat exchange effectiveness of holes ($\in_h$), back surface of the absorber plate ($\in_b$) and at the face of heated boundary ($\in_f$) presented as;

$$\in_{HX} = 1 - (1 - \in_f)(1 - \in_h)(1 - \in_b) \tag{10}$$

The heat exchange effectiveness [16] can be used in ranges of variables:

$$0.028\ \text{m/s} \le v \le 0.083\ \text{m/s},\quad 0.0\ \text{m/s} \le u \le 5.0\ \text{m/s},$$
$$0.007\ \text{m} \le P \le 0.024\ \text{m},\quad 0.0008\ \text{m} \le D \le 0.0036\ \text{m},$$
$$0.0006\ \text{mm} \le t \le 0.0065\ \text{and}\ 0.115\ \text{W/mK} \le k200\ \text{W/mK}.$$

The results are quite comparable with work published by Kutscher [13].

An experimental study [31] is carried out to study the effect of wind on thermal performance of TSC. It is reported that TSCs are not well suited for high rise residential buildings due to small area and low flow rate. Also some very significant conclusions are made, e.g. Hourly efficiency was found to be independent of incident solar radiation for radiation level above 200 Wh/m^2. It is being proposed that a laminar boundary layer thinner that the diameter of the perforations in the collector cladding exists and can be used for the modelling of system performance.

Using mathematical modelling [34] carried out sensitivity analysis for hybrid TSC and TSC integrated with glass plate. High absorbing efficiency (82%) can be achieved by combining glass plate collector to TSC. Biona et al. [35] had generated performance curves for TSC using mathematical modelling. Performance curves showed that collector efficiency and temperature rise varied linearly with the plenum depth showing a directly proportional relationship. Also collector efficiency tends to decrease with increasing hole diameter for plates with small (5 mm) pitch distances.

As the thickness of the absorber plate increases the performance curves become more parallel to each other for different hole diameter. Also for less plate thickness efficiency almost becomes independent of the approach velocity. Conclusions made can be controversial as wind effect; height of collector can also be significant factor while considering performance curves for plate with less thickness.

Leon and Kumar [15] presented the details of a mathematical model for UTC using heat transfer expressions for the collector components, and empirical relations for estimating the various heat transfer coefficients. The parametric studies were carried out by varying the porosity, airflow rate, solar radiation, and solar absorptivity/thermal emissivity, and finding their influence on collector efficiency, heat exchange effectiveness, air temperature rise and useful heat delivered. The results [15] indicated that the pitch has a stronger influence on heat exchange effectiveness than on efficiency.

Table 2
Pros/Cons of RET Screen and Swift.

Parameter	RET Screen	Swift
Use of weather data	Less accuracy due to monthly data	Hourly data
Comparison between the existing building without TSC and refurbished building with TSC?	Yes	No
Calculation algorithm, i.e. manual, of software provided?	Yes	No
Applicable for various types of buildings?	Yes	Limited for industrial building, agricultural buildings with TSC.
Consideration for the specific parameters of transpired solar collectors?	Limited	Yes
Azimuth	Yes	Limited
Wind sheltering	No	Limited
Canopy type and colour	No	Limited
Exhaust flow rate and location	No	Limited

Building integrated photovoltaic TSC performance is different than stand alone system [21]. Experimental and mathematical modelling [Anderson] has shown that the collector base material made little difference to the thermal efficiency of the BIPVT. It is also being suggested [21] that lower cost materials, such as steel, could be utilised for these systems. Prototype of BIPV/T and UTC systems for building facades has been developed [21] to study the ratio of PV coverage. The ratio of PV coverage may be selected based on the fresh air heating needs of the building. The combination of UTC with PV is promising for building applications where there is significant need for ventilation in winter. The value of generated energy for BIPV/T system is 7–17% higher than a TSC without PV.

In an experimental study [37] wind velocity was found to be the main factor affecting the energy recovery efficiency of the TSC irrespective of level of solar radiation. The experimental studies validates many models stating that efficiency of TSC is irrespective of solar radiation or affect performance of TSC marginally.

4.2. Simulations

RET Screen [42] and Swift [43] are two major simulation tools available in the market. A critical analysis has been carried out to find the pros/cons of widely used tool Swift and RET Screen for transpired solar collector presented in Table 2.

A mathematical model based upon Eq. (9) is also developed to compare the results of RET Screen and Swift simulation tools. Test condition for comparison of simulation tool is given below (Table 3);

Table 3
Case study conditions for comparison of models.

Parameter	Case 1	Case 2	Case 3	Case 4
Stratification	22 °C	22 °C	22 °C	22 °C
Indoor set temp.	19 °C	19 °C	19 °C	19 °C
Max. Supply (delivery) temp	28 °C	28 °C	35 °C	35 °C
Min. Supply (delivery) temp	15 °C	15 °C	15 °C	15 °C
Collector size	200 m^2	200 m^2	100 m^2	100 m^2
Flow rate	5400 m^3/h	7200 m^3/h	5400 m^3/h	7200 m^3/h

Fig. 11. Comparison of solar heating delivered from different models.

- Weather data: Cardiff airport
- Floor area: 3000 m^2
- Roof area: 3000 m^2
- Collector depth: 0.1 m
- Azimuth: South
- Tilt: 90° wall
- Building size: 100 m × 30 m × 15 m ($L \times W \times H$)
- Operation schedule: 7/24.

Test results for heating delivered are compared and shown in Fig. 11. Heating delivered predicted by the Swift software program is much higher than the other software programs. The overestimation of the Swift is due to abnormally large amount of savings in the summer periods, which has lower heating degree days.

TRNSYS is another simulation tool used widely [20,25] for the simulation study of transpired solar collector. Delisle and Collins [20] studied transpired solar collector systems integrated with PVs and analysed the effect of absorber shape on performance. Delisle and Collins [20] not only studied PVs integrated into transpired solar collector system, but also investigated the corrugated solar collector in detail. The effect of collector shape on absorbed radiation affected by shading in relation to the shape was studied by precise mathematical modelling. All these considerations were taken into account to investigate the thermal performance of the system combined by PVs and TSCs.

Summers [25] used TRNSYS to predict energy savings resulting from the active solar gain, the recaptured wall heat loss and reduced wall heat loss. Parametric studies for system operation are also carried out. Further the analysis is extended to find economic viability of using transpired solar collector in different sectors, e.g. commercial, residential, agricultural and industrial (Fig. 12).

To validate the accuracy of the TSC plate model [25], TRNSYS simulations of the National Solar Test Facility (NSTF) collector were performed actual weather data from Madison, WI. The air temperature rise ($T_{plen} - T_{amb}$) is plotted for every hour of the year for which the ambient temperature is between 20 and 25 °C. Variations in the conditions (e.g. sky temperature) cause the scatter in the results. In Fig. 12, it is important to note that the experimental curve fits are the lines, and the simulation results are the data points.

Various authors have also used commercial CFD code named TASCflow 2.2 to study performance of TSC [28,30,32,33]. Flow distribution analysis using CFD is carried out by Gunnewiek et al. [28]; TASCflow 2.2 simulation is used for analysis. Authors presented a 2D version of the code, and apply it to the problem of predicting the flow distribution in still air (no wind) conditions a situation well treated by a 2D code. Further analysis is [32] extended the earlier study from no wind conditions and developed simulation codes for TSC performance in wind. Various building orientations were examined, at a wind speed of 5 m/s. The wind was found to reinforce those factors that tend to produce outflow, and in light of this study, the recommended minimum suction velocity required to avoid outflow has been raised from about 0.0125 m/s to about 0.03 m/s, depending on the building shape. The wind has a pronounced effect on the velocity distribution, but not so large an effect as to negate operating the collector under windy conditions. The main effect is to raise the suction rate needed to avoid reverse flow, from about 0.0125 m/s under typical operating conditions, to about 0.017 m/s for long buildings with the collector facing into the

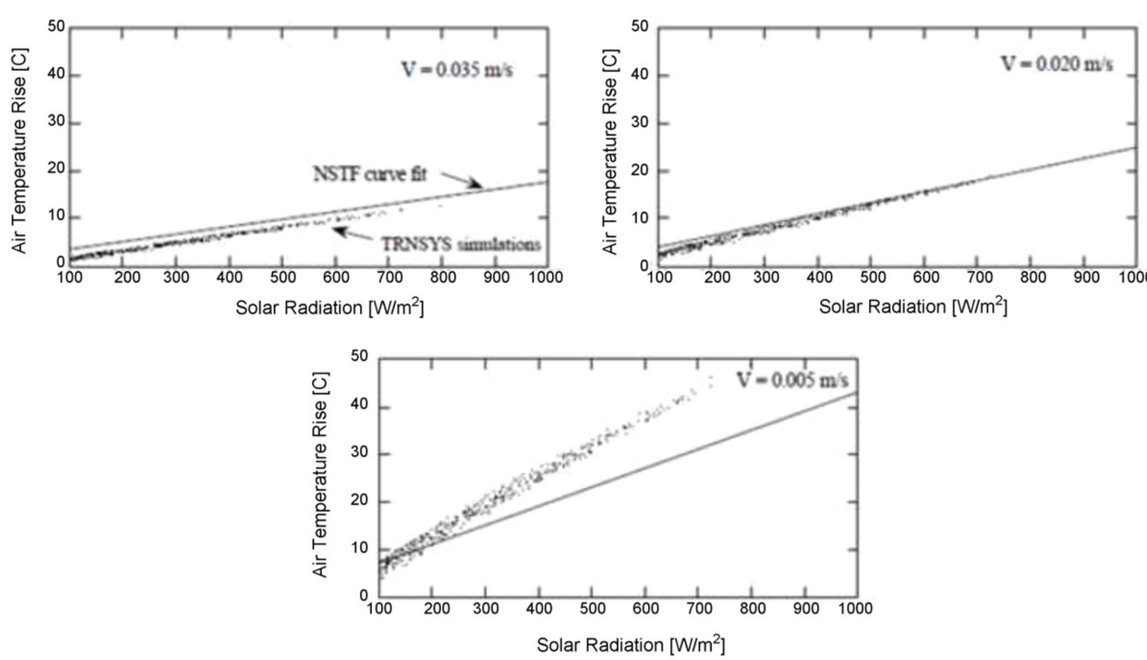

Fig. 12. Air temperature vs solar radiation at different approach velocity [25].

Table 4
Comparison of parametric study for different study.

Parameter	Study/results
Effect of perforation diameter and pitch	• For a constant airflow rate and solar radiation, air temperature rise increases with decreasing [15] pitch–perforation diameter-flow rate combination. • Heat exchange effectiveness decreases with increasing pitch, perforation diameter and approach velocity [44]. • For a constant airflow, heat exchange effectiveness and efficiency decrease with increasing pitch; pitch has a stronger influence on heat exchange effectiveness than on efficiency [15]. • For a particular pitch, any change in perforation diameter affects the heat exchange effectiveness only moderately [15].
Effect of absorber porosity	• For a constant pitch, increasing the porosity marginally decreases the heat exchange effectiveness and collector efficiency [15]. • 28% of the ultimate temperature rise of air occurs in holes [16].
Influence of solar radiation and airflow rate	• Solar radiation levels do not influence collector efficiency significantly [15]. • Efficiency can slightly increase or decrease with variations in radiation levels [24]. • Efficiency decreases with increasing delivery air temperatures [45]. • Collector efficiency decreases with increasing delivery air temperatures [15].
Effect of approach velocity	• At constant solar radiation, with increasing approach velocity, collector efficiency increases while HEE decreases [15]. • Efficiency increases with increasing approach velocity [38]. • To get high efficiency, the average approach velocity should be small, especially in large area collectors with non-uniform flow, with approach velocity higher at the bottom [28]. • For approach velocities greater than 0.05 m/s, efficiencies are nearly constant [38]. • Collector efficiency rises rapidly between approach velocities of 0.009 and 0.014 m/s, and moderately thereafter. For approach velocities greater than 0.03 m/s, efficiency is nearly constant [15]. • Delivery air temperature and heat delivered decreases with increasing approach velocity. The rate of decrease in heat delivered is lower at lower approach velocities [15].
Effect of absorptivity and emissivity	• Solar absorptivity has a significantly larger effect than emissivity [46]. Solar absorptivity has a stronger effect on efficiency than the thermal emissivity [15]. At high delivery air temperatures, emissivity has a significant impact on collector performance [45]. • The effect of emissivity on the heat output and therefore efficiency is significantly high at high delivery air temperatures [15].

wind, to about 0.026 m/s for cubical buildings with the collector facing into the wind, and to about 0.039 m/s for a cubical building with the wind incident on the collector at 45°. These numbers are for a wind speed at building height of 5 m/s, which is a higher than average wind speed for most locations.

An important parameter fixing the collector's efficiency is the heat exchange effectiveness, once effectiveness is known, finding the collector efficiency is straightforward. The effectiveness depends on the wind speed, the suction velocity, and the plate geometry. Arulanandam et al. [30] determined the effectiveness by CFD, for conditions of no wind. The strongest effect on effectiveness was observed for Reynolds number; the next strongest effect was observed for plate porosity and plate admittance. The plate admittance represents the ability of the plate to conduct heat. Because of the high conductive coefficient near the hole associated with the high velocities there, the region of the plate surrounding the holes takes up a lower temperature than the rest of the plate. Heat from the outer regions of the plate is therefore conducted towards the hole and thus increases the heat exchange effectiveness.

Gawlik and Kutscher [33] used Fluent to study heat losses because of wind through a corrugated TSC. It has been reported that boundary layer dynamics is very important to study heat loss coefficient. For corrugated transpired solar collectors, convective losses to the surrounding must not be neglected. Empirical studies of large UTC systems showed that the efficiency of UTCs is depending on the wind speed. Therefore, the Nusselt number was determined numerically and experimentally. Depending on the operating conditions, attached or separated boundary layers can occur at the absorber plate. It is been reported that thermal losses for separated boundary layers are considerably greater than for attached layers.

CFD simulation tools like TASCflow and Fluent have been used in the research to find out the impact of wind flow around the collector and also to study different shapes of collector. These simulations are capable of providing very useful and accurate information if boundary layers conditions are provided accurately. TRNSYS is basically used by researchers to study the overall performance of TSC and also to do parametric analysis.

4.3. Parametric study

Parametric sensitivity is very important analysis for the study of dependence of various parameters in the performance of TSC. Table 4 presents comparison of parametric study from literature. Parameters like perforation diameter and pitch, absorber porosity, solar radiation and airflow rate, approach velocity, absorptivity and emissivity are most important among many others. It is being reported that for constant air-flow and solar radiation, rise in air temperature increases with decrease in perforation diameter [15]. Similar conclusions are also made [44] showing heat exchange effectiveness (HEE) decreases with increase in pitch, perforation diameter and approach velocity.

As the performance of transpired solar collector depends significantly on specific location and application, it is difficult to compare different cases. Heat exchange for holes [16] nearly contribute 28% of the overall temperature rise of air whereas [15] it is also reported that heat exchange effectiveness changes marginally while changing the porosity of the collector. But the case may be different for different thickness of the collector [31].

Sensitivity for solar radiation to effect the efficiency of TSC is not significant as reported by various researchers [15,24,45]. Approach velocity is also very significant factor, increase in approach velocity increases collector efficiency. Whereas at low approach velocity the changes in efficiency with approach velocity are quite significant. But as approach velocities increases to certain level effect on efficiency becomes negligible. Colour of the collector is also very important factor influencing the performance of TSC, solar absorptivity has a significantly larger effect than emissivity on the collector performance [15,45,46].

5. Conclusions

The increasing European Union legislation on building and energy services provides a unique opportunity to analyse various renewable energy technologies, which are low in cost and highly efficient. By reviewing the state of art transpired solar collectors, it is found that TSCs are ideal to be used in the buildings. Literature

review, theory, experimental analysis has shown that high efficiency can be achieved using TSC. The TSCs can also be integrated with other technologies, e.g. heat pump and PV. The literature has shown that the most critical factors affecting TSC efficiency are wind velocity, flow rate, porosity, absorptivity and porosity.

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